An overview of soil-water characteristic curves of stabilised soils and their influential factors

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Review

An overview of soil–water characteristic curves of stabilised soils and their influential factors

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A B S T R A C T

Since unsaturated soil conditions are normally experienced above the groundwater table, most treated or stabilised soils for roadworks, earth dams' embankments, landfill sites, hydraulic barriers etc. could be regarded as existing in this region. The soil–water characteristic (or retention) curve (SWCC) is a useful conceptual tool by which an evaluation of unsaturated soil's property functions and corresponding macro-scale behaviour (strength, volume change, hydraulic conductivity, fluid flow, diffusivity, etc.) can be carried out. Hence, an examination of some of the various factors that could affect the hydraulic or water retention property of the stabilised soil is very vital both for laboratory studies and field practice. However, a thorough assessment of the water retention behaviour of stabilised soils can be understandably limited sometimes. This could be partly due to some of the perculiar conditions associated with soil preparation methods, soil type, soil-stabiliser mix proportion used, curing conditions, method of compaction, durability assessment modalities and other logistical issues surrounding either laboratory instrumentation or in-situ application. This article presents a critical and comprehensive review of these factors on the stabilised soil's water retention behaviour and also provides a systematic understanding of the mechanisms of stabilisation occurring at the micro- and macro-mechanical levels. Recommendations are also made to stimulate further discussions on the synthesis of SWCC of stabilised soils vis-à-vis factors influencing them with possible interpreted engineering behaviours such as shear strength and soil consolidation.

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1. Introduction

In recent years, the engineering behaviour of collapsible, expansive, residual and compacted soils existing under unsaturated conditions for any given period has been effectively interpreted by considering the impact of suction as an independent stress state variable (Alonso et al., 1999; Eyo et al., 2020a; Gens and Alonso, 1992; Vanapalli et al., 2014; Zhai et al., 2019; Zhai and Rahardjo, 2015). The soil–water characteristic (or retention) curve (SWCC) is one of the useful concepts by which an evaluation of unsaturated soil's property functions and its corresponding hydraulic characteristics can be determined. For instance, by using the SWCC, estimations can be made of soil–water storage, field capacity and soil aggregate stability in agricultural engineering (Fuentes et al., 2009; Patil and Rajput, 2009; Rawls et al., 2003). Meanwhile, in geotechnical engineering, it is also widely used to evaluate and predict the failure of foundations and slopes due to volume change (collapse or swelling) during rainfall (Rao and Revanasiddappa, 2000; Zhou et al., 2012). SWCC is defined uniquely by the relationship between the mass of moisture present in a soil and the corresponding energy state or suction within the pore water.

Since unsaturated soil conditions are normally experienced near the ground surface (or the active zone), most treated or stabilised soils for roadworks, earth dams, landfills, hydraulic barriers etc. could be regarded as existing in this region (Abbey et al., 2019, 2020; Al-Malack et al., 2016; Amadi and Osu, 2016; Eyo et al., 2018, 2020b; Sani et al., 2020). Hence, the hydraulic characteristics of stabilised soils can also be interpreted using unsaturated soil mechanics concepts through the SWCC.

2. Background

2.1. Evolution of the soil–water retention concept

The theoretical concept and framework proposed for unsaturated soil mechanics has been established over the past few decades. The present understanding of the SWCC in particular has been made possible by numerous researchers and some important developments in soil physics dating back to the late 1800s (Barbour, 1998). One of the foremost descriptions of water distribution and flow in soil voids was carried out by depending on elementary capillary theory (Childs and George, 1948; Gardner, 1961; Lambe, 1958; Richards, 1931; Terzaghi, 1943). Geotechnical engineers in the 1950s and 1960s needed to further comprehend and apply the flow concept to unsaturated soils but one of the many prevailing misconceptions was that water flow could only occur within the capillary zone and in the range of positive pore-water pressure. Lambe (1958) made an attempt at finding a single soil property flow in the zone of negative pore-water pressure by using "capillary head" to describe "wetting" and "draining" conditions.

Gardner (1961) related the concept of water potential to the coefficient of permeability which then gave rise to the application of non-linear continuous function for the description of seepage through unsaturated soils. However, the solution for such non-linear problems needed powerful computing capabilities which at the time were either rare or non-existent.

Later, Fredlund and Morgenstern (1977) formulated the stress state theoretical concept as a basis for describing some of the problems in geotechnical engineering involving unsaturated soils. Following on from this, principles based on macroscopic multiphase continuum mechanics for defining stress state variables were advocated.

In the 1980s and 1990s, the estimation of non-linear unsaturated soil property functions for nearly all kinds of geotechnical engineering problems would be based mostly on the SWCC as an interpretative tool. Various prediction models for the estimation/-calculations of the permeability function in unsaturated soils were proposed. Out of the three groups of models suggested (macroscopic, empirical and statistical), the statistical model would become the most accurate yet rigorous to apply (Leong and Rahardjo, 1997). However, Romero (2013) and Romero et al. (1999) opined that the statistical concept was only limited for predictions of permeability function of soils whose inter-aggregate porosity governs suction. Nevertheless, alternative methods incorporating new technologies and some programming capabilities have been developed in recent years to estimate the permeability function (Beckett and Augarde, 2013; Zhai et al., 2019; Zhai and Rahardjo, 2015; Zhou et al., 2014).

Besides fluid flow, SWCC has also been applied over the years to problems in geotechnical engineering that involves coupled and uncoupled estimation of shear strength, heat flow, volume change, etc. (Al Aqtash and Bandini, 2015; Gatabin et al., 2016; Vanapalli et al., 1996; Zhai et al., 2020a).

2.2. Key terminologies and description of SWCC

The stress state variable of greatest significance to the mechanics of unsaturated soils is soil suction. Three components of soil suction are usually determined or measured namely: matric suction, osmotic suction and total suction. Matric suction is defined simply as that suction component which relates to the height to which water can be drawn or sucked up (i.e. capillary rise) into an unsaturated soil. Osmotic suction is that component resulting from the differences in the concentration of salts at different locations in the soil water. Total suction is mathematically the sum of matric and osmotic suctions and can simply be quantified as the relative humidity just immediately adjacent to the surface of water.

The SWCC is typically sigmoidal in shape for a soil and describes the relationship between soil suction and moisture content. Some of the other terms used to refer to the water content-suction relationship are moisture retention curves or retention curves, soil moisture retention curves, soil suction curve and water retention curves (Aubertin et al., 2003).

Due to a phenomenon called hysteresis, the SWCC can be presented as either a drying (desorption or desaturation) or wetting (sorption or saturation) curve. However, for ease of description and measurement of its features, the drying curve is mostly used. Fig. 1 shows a typical SWCC with its three distinct stages - the transition stage, boundary effect stage, and the residual stage. The slope of the curve on which is found the inflection point separates two key components namely: the air entry value (AEV) suction and residual conditions (residual suction or residual water content). The AEV (or bubbling pressure) represents the suction value at which air begins to enter the soil's largest voids. The suction at the residual condition is termed the residual suction value (RSV) or residual soil suction and signifies the suction corresponding to the residual moisture content. The residual moisture content is the minimum moisture content beyond which there is no appreciable change in moisture with suction. It should be noted that if the wetting curve is considered then the point referred to as the water-entry value (WEV) is defined as the suction at which there is a significant increase in the water content as the wetting progresses.

2.3. Equations or models for the SWCC

Several proposed direct and indirect methods of measurement and determination of SWCC have been suggested. The resulting moisture content-suction data derived from direct measurements are plotted and used to obtain equations or mathematical models with curves fitted through the data points. Some of the more relevant and commonly used mathematical functions are presented in Table 1.

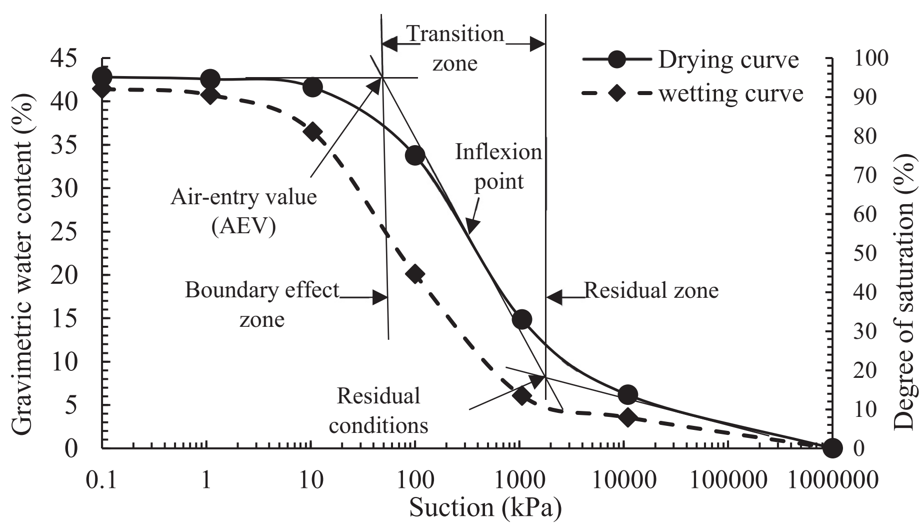

Fig. 1. Typical features of the soil–water characteristic curve (SWCC) (modified after Vanapalli et al. (1996)).

Table 1
Summary of commonly referenced soil–water characteristic curve fitting models.

Reference	Mathematical fitting model	Parameter description
(Fredlund and Xing, 1994)	$\frac{\theta_w}{\theta_s} = \left[1 - \frac{\ln\left(1+\frac{\psi}{h_r}\right)}{\ln\left(1+\frac{10^6}{h_r}\right)}\right]\left[\frac{1}{\ln\left\{e+\left(\frac{\psi}{a}\right)^n\right\}^m}\right]$	Where: θ_w = gravimetric water content (%) θ_s = saturated volumetric water content (volumetric water content at suction ψ = 0) φ = soil suction (kPa) S_e = effective saturation for $\psi < \psi_c$ S_e = 1 for $\psi \geq \psi_c$ ψ_c, ψ_o α = parameters h_r = fitting parameter, which is a function of the suction at the residual water content e = exp (1), base of natural logarithm a = fitting parameter, which relates to the air entry value of the soil (kPa) n = fitting parameter, being a function of the slope of the SWCC m = fitting parameter, being a function of the residual water content λ = pore size distribution index erfc = complementary error function
(van Genuchten, 1980)	$\frac{\theta_w}{\theta_s} = \left[\frac{1}{\left(1+\left(\frac{\psi}{a}\right)^n\right)^m}\right]$	
(Gardner, 1958)	$\frac{\theta_w}{\theta_s} = \frac{1}{\left(1+\left(\frac{\psi}{a}\right)^n\right)}$	
(Brooks and Corey, 1964)	$\frac{\theta-\theta_r}{\theta_s-\theta_r} = \frac{\psi_a}{\left(\frac{\psi}{a}\right)^\lambda}$	
(Kosugi, 1994)	$S_e = \frac{1}{2}\mathrm{erfc}\left\{\frac{In\left[\left(\psi_c-\psi\right)/\left(\psi_c-\psi_0\right)\right]-\sigma^2}{2^{1/2}\sigma}\right\}$	
(Burdine, 1953)	$\frac{\theta_w}{\theta_s} = \left[\frac{1}{\left(1+\left(\frac{\psi}{a}\right)^n\right)^{\left(1-\frac{2}{n}\right)}}\right]$	

2.4. SWCC of stabilised soils

Analyses and evaluation of the moisture retention characteristics of stabilised soils have been carried out variously in literature. However, a thorough assessment of the water retention behaviour of the stabilised products seems understandably limited owing to the peculiarity of conditions associated with the method of preparation adopted, soil type, the soil-stabiliser mix proportion used, curing conditions followed, compaction method used, durability assessment modalities and other logistical issues surrounding either laboratory instrumentation or in-situ application.

3. Aim and scope of review

The aim of this study is to present a critical and comprehensive review of stabilised soil's water retention behaviour with the objective of providing a systematic understanding of the mechanisms of stabilisation both at the micro- and macro-mechanical scales. Also, in order to stimulate further research, recommendations are made by including areas not previously covered in literature.

Depending on the objective of a given research, it may not be uncommon for different authors to adopt varying methods and procedures for the determination of SWCC of stabilised soils. Therefore, in this study, an overview of the effect of the adopted binders or stabilisers, testing conditions and soil's intrinsic properties are firstly presented based mainly on their individual merit rather than on those of the equipment or technique used in the derivation of the SWCC. Later, discussions are provided, and necessary comparisons drawn on how suction measurement or its application might influence the SWCC of stabilised soils. Nonetheless, Table 2 includes a summary of the materials, equipment and procedures followed by most of the authors (cited in this article) for the determination of SWCC of stabilised soils.

4. Effect of stabiliser type and proportion

The two categories of stabilising agents namely: calcium-based and non-calcium-based stabilisers have been utilized in various researches to improve as well as study the behaviour of soils as recently reviewed by Behnood (2018). The calcium-based traditional stabilising agents (such as cement, lime, pulverised fuel ash or fly ash, ground granulated blast furnace slag, etc.) when added to the natural soil would cause initial hydration, (and probably carbonation) leading ultimately to the formation of pozzolanic compounds which produces a cementation effect as time progress.

Table 2
Summary of material property and suction technique/procedure.

Source	Soil type	PI	USCS	Binder	Suction measurement/ application technique	Suction range	Category of suction method	Equilibration period
(Aldaood et al., 2014)	Clay	8%	CL	Lime	(a) Tensiometric plates (b) Osmotic membrane (c) Vapour equilibrium	(a) 10–20 kPa (b) 100–1500 kPa (c) >1500 kPa	(a) Direct (b) Direct (c) Indirect	(a) 21 days (b) 28 days (c) $\geq$ 28 days
(Al-Mahbashi et al., 2020)	Clay	22–38%	CH	Lime & polypropylene	(a) Pressure plate (b) Filter paper	(a) 0–1500 kPa (b) >1500 kPa	(a) Direct (b) Indirect	(a) 24 h (b) 20 days
(Al-Taie et al., 2019)	Clay	50.5%	CH	Lime	(a) Hyprop (tensiometers) (b) Filter paper (c) Dewpoint potentiameter	(a) 0–1500 kPa (b) NS (c) 1500–60,000 kPa	(a) Direct (b) Indirect (c) Indirect	NS
(Bilsel and Oncu, 2004)	Clay	11%	ML	Lime	Filter paper	> 10 kPa	Indirect	7–10 days
(Elkady et al., 2015)	Clay	77%	CH	Lime	(a) Pressure plate (b) Filter paper	(a) 0–1500 kPa (b) >1500 kPa	(a) Direct (b) Indirect	(a) 24 h (b) 21 days
(Hoyos et al., 2007)	Clay	31%	CH	Cement (type I/II)	(a) Pressure plate (b) Filter paper	(a) 0–1500 kPa (b) >1500 kPa	(a) Direct (b) Indirect	(a) 24 h (b) NS
(Khattab and Aljobouri, 2012)	Clay	28%	CH	Lime and cement	(a) Vapour equilibrium (b) Osmotic solution	(a) 2700–325,000 kPa (b) >325,000 kPa	(a) Indirect (b) Direct	(a) 45 days (b) 21 days
(Lin and Cerato, 2012)	Clays	34–44%	CH	Fly ash	Pressure plate	0–1500 kPa	Direct	24 h
(Mavroulidou et al., 2013)	Clay	38%	CH	Lime	Filter paper	> 10 kPa	Indirect	NS
(Puppala et al., 2006)	Clays	22 – 32%	CL	Fly ash, Bottom ash, Polypropylene, Nylon	Pressure plate	0–1500 kPa	Direct	24 h
(Stoltz et al., 2012)	clay	42%	CH	Lime	(a) Vapour equilibrium (b) Osmotic solution (c) Filter paper	0–292,000 kPa (imposed)	(a) Indirect (b) Direct (c) Indirect	7 days
(Tedesco and Russo, 2010)	Silt	9%	CL	Lime	Pressure plate	0–1500 kPa	Direct	4 days
(Wang et al., 2015)	Silt	23%	CH	Lime	Dewpoint potentiameter	Entire range	Indirect	NS
(Wen et al., 2015)	(a) Clay (b) Silt	(a) 13.9% (b) NS	CL	Fly ash	Dewpoint potentiameter	Entire range	Indirect	24 h
(Yang et al., 2011)	Clay	NS	CH	Lime & Fly ash	Pressure plate	0–1500 kPa	Direct	NS
(Zhang et al., 2017)	Clay	38%	CH	Lime	(a) Filter paper (b) Suction-control Triaxial Cell (c) Pressure plate	(a) NS (b) 550–650 (500–0-550 kPa cycle) (c) NS	(a) Indirect (b) Direct (c) Direct	(a) NS (b) 7 days (c) 7 days
(Zhang et al., 2018)	Sand	NS	(SM-CL)	Cement & GGBS	Centrifuge		Direct	10 h

NS = Not stated, CL = low plasticity clay; CH = highly plastic clay; ML = low plastic silt; SM = silty sand.

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This phenomenon is expected to influence the soil water retention not least, its mass-volume properties (Croce and Russo, 2003). However, depending on only the type and amount of the calcium-based stabiliser used (without considering other testing conditions and procedures), these effect could vary. Thudi (2006) compared the effect of cement (type I/II) and hydrated lime on the volumetric water content of the stabilised soil. The initial volumetric moisture was found to have decreased as the proportion of the cement and lime increased especially at the low suction range. Moisture retention of the cement-stabilised soil was observed to be slightly greater than that for the lime-treated soil the reason which was credited to the finer cement particles. Puppala et al. (2006) also arrived at the same conclusion by using a finer stabiliser (fly ash) compared to coarser bottom ashes in their investigations.

On the other hand, non-calcium-based stabilisers such as polymers or fibres if used as sole stabilisers, may not change or induce chemical reactions on the soils to cause modifications in their particle sizes vis-à-vis their volumetric properties owing to their innate physical or mechanical characteristics (Puppala and Musenda, 2007). Hence, some of the non-calcium type stabilisers may have to be activated by or used in conjunction with the calcium-based hydraulic ones. Puppala et al. (2006) and Al-Mahbashi et al. (2020) confirmed this notion in their investigations. Puppala et al. (2006) combined two classes of fly ashes (both Class F) with fibres and bottom ashes (non-hydraulic) with fibres (non-hydraulic) to study the behaviour of the SWCC. Fly ash and fibre stabilizer combinations reduced the volumetric moisture contents compared to the untreated soil whereas changes in the moisture contents of the bottom ash and fibre combination were smaller.

5. Stabilised soil's SWCC parameters

As mentioned earlier, the air-entry value (AEV) and residual suction value (RSV) are the main transition points on the SWCC when considering soil suction and water content ranges that can be encountered in practice.

Most authors agree that since stabilisation results in a well-bound and closely packed particle sizes of the mixed product, the AEV should increase with an increased stabiliser content due to the binding effect of the stabilisers used. Hoyos et al. (2007) investigated the SWCC of a stabilised expansive clay by adding 2, 5 and 10% of cement (by dry weight of soil) to the soil. The test results indicated an increase in the AEV ascribed to the greater bonding effect and pore reduction caused by the treatment. More so, it has been observed that increased stabiliser quantity can affect AEV. Yang et al. (2011) reported an increase in the AEV and hence, moisture retention visually observed as a flattening of the slope of the SWCC as the amount of lime and fly ash used in the stabilised expansive soils increased. On the other hand, Thudi (2006) showed that same quantities of different hydraulic stabilisers used does have different effects by comparing cement and lime. It was concluded that an increase in the percentages of the stabilisers increased the AEV however, the AEV obtained from lime treatment was relatively lower than those from cement treatment for the same quantity of both stabilisers used.

On the other hand, soil treatment has also been observed to increase the RSV (Khattab and Al-Taie, 2006; Khattab and Aljobouri, 2012; Yang et al., 2011). A decrease in the RSV was however indicated in the work of Thudi (2006) when the dosages of cement and lime used separately in the treatment of the expansive soil increased. The exact behaviour of the treated soil at the residual conditions are not clearly known even though Nelson et al. (2015) have noted that the residual condition is relative to the type or nature of the untreated soil (clay, silt or granular). For instance, an expansive or clayey soil lacks a distinct value for the residual moisture content condition.

6. Conditions before and during testing

6.1. Effect of initial dry density and water content

Zhang et al. (2017) studied the SWCC of 4% lime treated London clay at varying degrees of initial (as- compacted) dry densities and water contents as shown in Figs. 2 and 3. Both figures are modified in this paper with the suction points fitted through with the van Genuchten (1980) model in order to make for easier comparison. The SWCC of Fig. 2 were derived from samples compacted dry of optimum and subjected to saturation (water-cured) prior to filter paper suction measurements. Meanwhile, for the untreated sample, the desorption curve was determined starting from the as-compacted conditions without prior wetting/saturation) hence, it has a much lower gravimetric water content at the beginning. At the same initial moisture content (w), it is observed from Fig. 2 that the treated samples with higher initial dry densities (DD) are located higher (slightly more water retention) than the respective SWCCs of samples with lower initial dry densities. Consequently, the suction corresponding to points of maximum curvature (indicating AEV) decreases with decreasing compaction dry densities. However, beyond this point, the slopes of (the desorption rate) appear to coincide, irrespective of dry density as similarly observed by Romero and Vaunat (2000).

Fig. 3 shows the SWCC of untreated and treated soils based on suction measurements using the filter paper from as-compacted conditions. Notice also that the SWCCs of the treated soil do not record the original (compaction) water contents (w) given that suction test was conducted 14 days after air curing. Therefore, the starting water contents on the SWCC are not the same as the respective water contents at compaction. However, it is observed from Fig. 3 that at the same values of compaction dry densities (DD), SWCC of the treated soil appear to be slightly different up to suction levels of approximately 1000 kPa beyond which convergence of the curves occur. The merging of the SWCCs at higher suctions indicates a relative insensitivity of the micropores of the treated soil to initial differences in as-compacted water content as are those of the natural soil (Romero and Vaunat, 2000; Salager et al., 2013). Higher degrees of retention are also noticed for the soils compacted wet of optimum than those compacted dry of optimum. This is due to the lower void ratios of the samples compacted wet of optimum which experienced a higher shrinkage (please refer to later discussions on volumetric response by Zhang et al. (2017)).

An interesting observation from studies on the initial water content and dry density is that their influence only seem significant at the near saturation portions of the SWCC whereby capillary forces are mostly present. As desaturation occurs, the influence of adsorptive and osmotic forces at high suction ranges are probably felt albeit at similar levels despite the differences in initial water contents and dry density. However, a validation of this notion can be made by stabilising the soils using other binder types and following different procedures in the determination of SWCCs of the stabilised soil.

6.2. Effect of compaction conditions

It was indicated by Vanapalli et al. (1999) that provided soil suction remains constant, soils compacted dry of optimum would exhibit lower water retention capacity compared to soil samples that are compacted at much higher water contents as already seen

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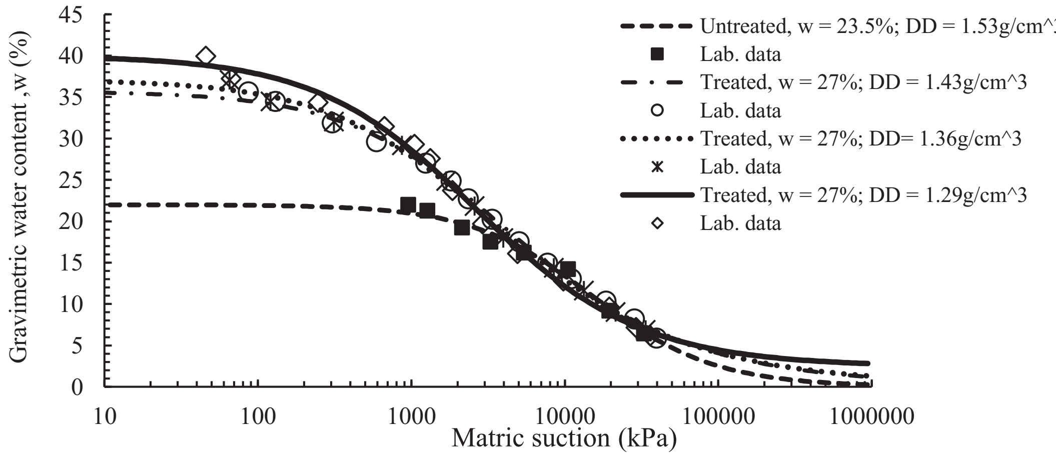

Fig. 2. Effect of dry density on SWCC of stabilised soil (modified after Zhang et al. (2017)).

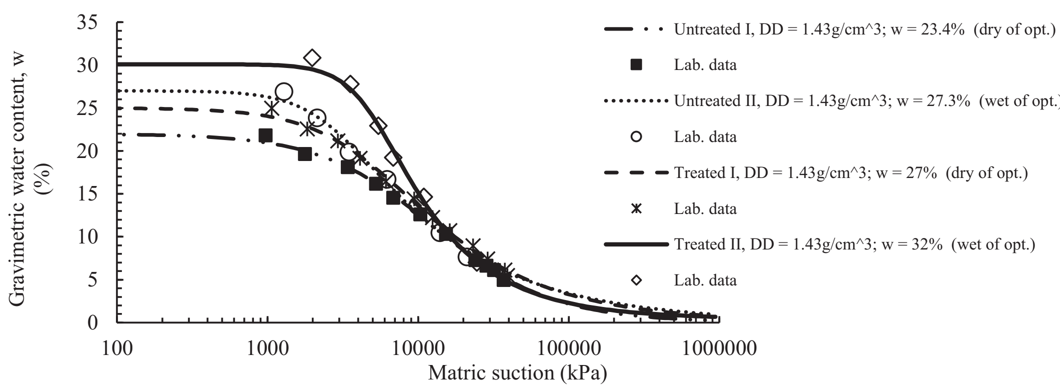

Fig. 3. Effect of initial moisture content on SWCC of stabilised soil (modified after Zhang et al. (2017)).

in Fig. 3. Khattab and Al-Taie (2006) investigated the impact of compaction conditions on SWCC of an expansive soil treated by lime (4% by dry weight of soil). It was similarly observed that for the treated soil, SWCC for the wet of optimum condition plots above (i.e. higher AEV and water retention capacity) the optimum and dry conditions. However, a slightly different result was obtained by Tedesco and Russo (2010) in their study given that the larger increment of water retention was accorded the dry of optimum condition for stabilised soil even though both the optimum and wet of optimum conditions of the stabilised soils stimulated greater water retention under the curing duration considered. Both Khattab and Al-Taie (2006) and Zhang et al. (2017) seem to agree that there is no difference in the behaviour of the SWCC at greater levels of suction, in other words, there appears to be the same inter-aggregate structure for the stabilised soils at higher suction. Vanapalli et al. (1999) had proposed that at higher values of suction, the moisture film of soils could be very thin as to become subjected to the effect of both osmotic and adsorptive force fields. This perhaps also explains why there may have been insufficient water to cause any further pozzolanic reactions at higher suction.

7. Stabilised soil curing

7.1. Curing duration

Khattab and Al-Taie (2006) investigated the impact of a 4% lime-stabilised soil, statically compacted at optimum moisture and cured for 7, 30, 60, 90, 120- and 150-days. The water retention (slope), AEV and the residual suction value were noticed to have increased with the duration of curing. However, due to a slowing down of the pozzolanic reaction as curing duration increased, only minimal and in some cases no distortions to the shape of the stabilised samples are observed. Elkady et al. (2015) ascribed the little effects of increased curing duration on the SWCC at certain moisture ranges to minute influences caused by the pozzolanic reaction on pore size distribution.

Tedesco and Russo (2010) did previously explained the effect of curing duration by conducting an investigation into a lime-stabilised soil with discussions of the findings through the mercury intrusion porosimetry (MIP) test. MIP is one of the techniques that is frequently adopted to study the microstructure and to predict the water retention properties of unsaturated soils (Romero and Simms, 2008). In using this technique, an absolute pressure is applied to a non-wetting fluid such as mercury in order to intrude the soil's empty pores. For pores having somewhat of a cylindrical shape and fissure-like micropores (i.e. parallel infinite sheets), the equation proposed by Washburn (1921) does apply as follows:

$$r = \frac{2T_s cos\alpha}{P}$$

where:

R = entrance pore radius (m)
T_s = surface tension of non-wetting liquid (which for mercury is 0.485 Nm^{-1})

α = contact angle of liquid-to-solid interface (which for mercury is 140^0)
P = difference in pressure between the fluid–solid interface (Pa).

Tedesco and Russo (2010) added 3% of the lime the soil and compaction same at optimum conditions while the curing was observed at 0, 7, 28 and 77 days. Increased duration of curing increased water retention of the stabilised soils in general. However, a slight reduction in the AEV occurred at 7 days of curing with no significant changes taking place at suctions higher than 100 kPa. With increased curing time (≥28 days), the moisture retention became higher at suction beyond 100kpa but with the AEV reduced. This was corroborated by Elkady et al. (2015) given that the air entry for their curing duration investigations (7 and 28-day cured samples) occurred at suction values beyond 1000 kPa but with no apparent difference in the moisture retention capacity (noted by similar slopes of their SWCC).

Fig. 4 shows the MIP test results (incremental and cumulative volume of mercury intruded) carried out by Tedesco and Russo (2010) and Tedesco (2006) to demonstrate the dependence of the SWCC on duration of curing. As observed in Fig. 4, lime reactions significantly modify the microstructural constitution of the natural soil. At 7 days curing duration, a visible alteration of the porosity of the stabilised specimens occurs accompanied by the development of pores of relatively large diameter ranging between 4 and 40 µm. However, this effect is seen to have been subsequently reduced as the curing reaches 28 days presumably due to the formation of inter-aggregate bonds by pozzolanic reactions which invariably means an increase in moisture retention as also alluded to by Khattab and Al-Taie (2006). As curing increases further, the frequency of the inter-aggregate pores does not seem to reduce as much. Notice also the similar pore frequency (0.01 µm to 0.2 µm) in Fig. 4a for all the curing durations. For the pores of the type of an ink-bottle typified by a smaller entrance radius than the dimension of its inner parts, intrusion may not occur until there is sufficient amount of pressure to force the mercury in the narrow neck. Upon depressurization of the ink-bottle pores, there is an entrapment of the mercury in the inner portion of the pore and upon drying, ink-bottle pores will act to retain water in the stabilised soil. A smaller narrow opening of the ink bottle suggests a higher suction is needed to cause the soil to desaturate.

Using ordinary Portland cement (OPC) and ground granulated ballast furnace slag (GGBS) as binders in the stabilised soil, Zhang et al. (2018) studied the SWCC of an uncompacted marine sediment stabilised by different quantities of the binders [4% OPC, 12% OPC and 12% (6% each)] of OPC and GGBS. The effect of curing under controlled temperature at 7, 28 and 56 days were analysed. For all the stabilised cases of the sediments studied, a notable dependence of the SWCC on the duration of curing was observed. When the duration of curing increased, the differences between the OPC-only stabilised soil and the partially substituted OPC-stabilised soil was obvious. Hence, at 28 and 56 days of curing, the initial volumetric moisture of the substituted OPC was much less and the slope of the SWCC became flatter (greater moisture holding capacity) than the OPC-only stabilised soil. Generally, the effect of curing times was less remarkable as the suction level increased beyond 100 kPa as also observed by Elkady et al. (2015) and Tedesco and Russo (2010).

Despite the obvious influence of curing duration on the SWCC particularly at lower ranges of suction as suggested in some of the forgoing studies, only minimal effects of the same were noticed by Stoltz et al. (2012) and Zhang et al. (2017) for almost the entire range of imposed suctions on treated soils. However, it was not very clearly stated what other factor would have affected their investigations.

7.2. Curing condition

Aldaood et al. (2014) included temperature as one of the environmental state variables that could possibly affect the water retention behaviour of a compacted 3% lime treated soil. Results of the samples cured under 20 °C and 40 °C showed an increase in the water holding capacity of the SWCC with temperature. According to Aldaood et al. (2014) this phenomenon occurred due to the acceleration of the chemical reactions in the soil-binder mix. The samples cured at 40 °C had finer pore size distribution compared to those cured at 20 °C. Furthermore, the effect of curing temperature was more significantly felt at suction levels below 1500 kPa. But it is important to also note that unlike the observations made by Aldaood et al. (2014) on the treated soil, water retention seems to decrease with an increase in temperature for the untreated soil (Villar and Lloret, 2004). Apart from the description which could be offered for the phenomenon occurring in either the treated and untreated soil namely, surface tension, soil fabric and fluid chemistry, etc., the contribution from curing under the given conditions could also have been the differences in the SWCC at low suction ranges. This is worth further investigations in future studies.

Zhang et al. (2017) studied the impact of curing method by subjecting lime-stabilised soils under water and in the air. Results indicated that although SWCC of the samples cured in water began with higher saturation degrees (having more water retention capacity) however, both the air and water-cured samples coincided at suction levels higher than about 1000 kPa. This seemed to have occurred in spite of the higher (full) saturation and lower void ratios achieved before the start of the desorption process.

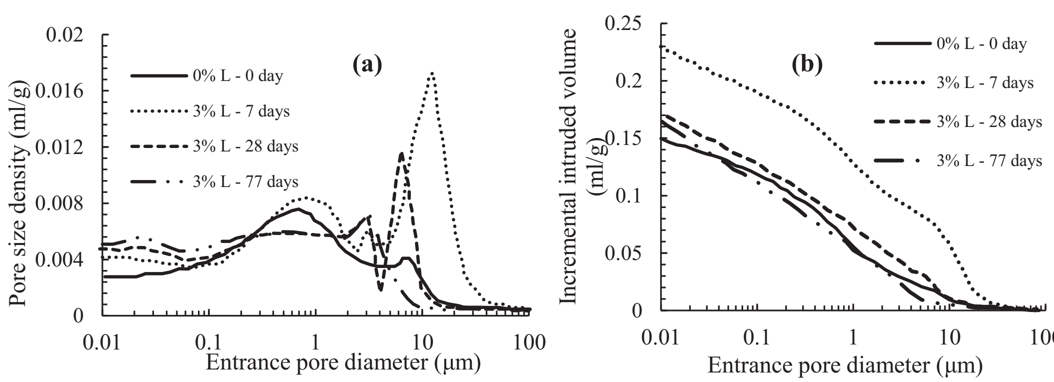

Fig. 4. MIP of specimens (a) pore size distribution (b) cumulative intruded volume of mercury (modified after Tedesco and Russo (2010)).

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8. Effect of stress state and history

Not many authors have studied the influence of effective stresses or loading of the stabilised soils under suction-controlled testing. Elkady et al. (2015) investigated the effect of stress history on the SWCC of lime-treated soils. Vertical stresses (7,100 and 600 kPa) were first imposed on the saturated stabilised-oedometer samples. After saturation, the stabilised samples were then transmitted to a pressure plate extractor for application of suction. The effect of the net vertical stresses on water retention ability of the 4% treated samples were more remarkable under the stresses of 100 and 600 kPa (Fig. 5a & b). It is noticed that samples tended to desaturate rather more readily under the 7kpa stress than at the higher stresses (100 kPa and 600 kPa) with increasing suction. (Please refer to later discussions on the corresponding volumetric changes to see the effect of stresses on the void ratio vs suction curves).

Using a suction-controlled triaxial apparatus (axis translation technique), Zhang et al. (2017) observed the influence of stress state on the SWCC of two air-cured lime-treated specimens under 100 kPa and 200 kPa mean net stresses. No noticeable points of maximum curvature or AEV existed on the desorption curves under both stresses. Indeed, the SWCC seemed to have continued to remain almost level with the initial gravimetric content (at the start of the drying process) during the entire suction ranges. This was attributed to the difficulty in saturating the tested samples subjected to a confining pressure with the triaxial apparatus. However, results obtained from another translation technique (pressure plate) showed a much higher saturation degree up to 200 kPa of applied suction and a relatively more conspicuous point of air entry compared to the triaxial cell device.

9. Effect of soil properties

Besides the factors demonstrated in the foregoing, several authors have also shown that the soil compositions and structural make-up can contribute to impact the hydraulic behaviour of the stabilised product.

9.1. Soil particle size

Two different aggregate sizes of the same soil treated by the addition lime (2% by dry weight of soil) were studied by Wang et al. (2015). The sizes of the powders used were 0·4 mm (or S-0·4) and 5.0 mm (or S-5). The compacted samples were cured up to a period of 90 days with the suctions inferred indirectly from mercury intrusion porosimeter (MIP). Results showed an increase in the water retention capacity of the cured S-0.4 and S-0.5 samples compared to the untreated soil. An evidence of the influence of the size of aggregates was noted for the untreated and treated soil at 90 days of curing with the water retention capacities of the soils of different sizes having large differences at the low suction range (<100 kPa) but a greater AEV for the S-0.4 aggregate-sized soil sample. Pore size distribution curves demonstrated a dependence of macro-porosity on soil aggregate sizes given that the smaller-sized aggregates (S-0.4) were observed to have formed a smaller modal size of the macropores. The treated S-0.4 samples at 90 days curing had lower total intruded void ratio (with higher AEV) compared to the S-0.5 sample (Fig. 6). An explanation of this phenomenon could be that the larger surface area of the S-0.4 aggregates was available for more effective reaction with lime and the formation of pozzolanic products (Tang and Cui, 2015). Another possible interpretation is that cementitious compounds

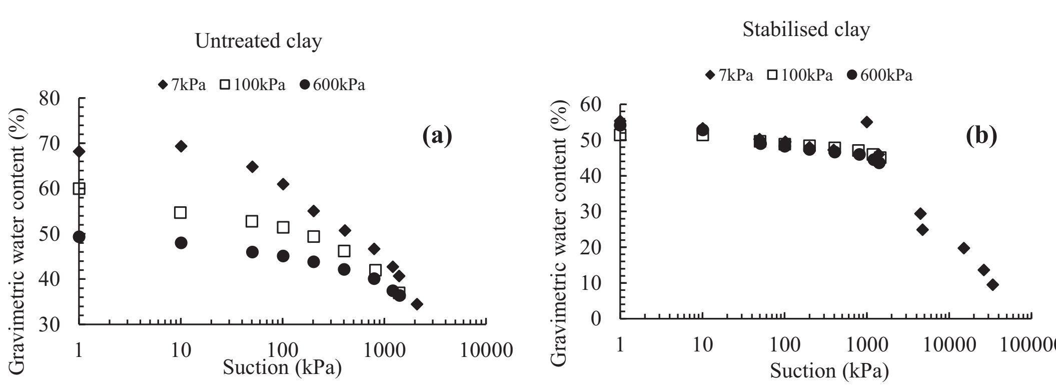

Fig. 5. Influnece of different net streses on SWCC (a) natural clay (b) stabilised clay (modified after Elkady et al. (2015)).

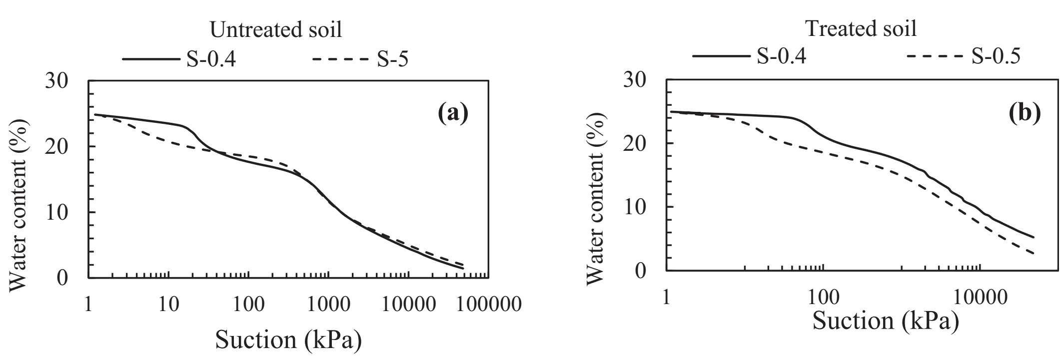

Fig. 6. SWCC of samples derived from MIP (a) effect of size of aggregates in the untreated soils (b) effect of size of aggregates on treated soils at 90 days (modified after Wang et al. (2015)).

which fill the macropores do effectively lead to a decrement of both the interconnectivity and size of these pores. Additionally, an increase in the amount of undetected pores can cause an increase in the water retention. On the other hand, less cementitious reaction is expected for the S-5 aggregate due to the smaller specific surface available for lime reaction hence, their macropore interconnectivity are not affected as much.

9.2. Presence of sulphates

In order to simulate the presence of sulphates in a soil and to assess its effect on the water retention behaviour of the soil stabilised or amended by lime, Aldaood et al. (2014) added varying quantities of gypsum (0, 5, 15 and 25%) to the soil. For similar suction pressures (especially below 1500 kPa), a phenomenal change in volumetric water content were observed for all the samples containing gypsum. The notable rise in volumetric water content with increase in the gypsum content was traced to a corresponding increase in osmotic pressure due to the salts present in the pore fluid - the occurrence of an osmotic gradient tends to attract more water into the soil-gypsum-lime matrix.

9.3. Soil pH and surface conductance

Lin and Cerato (2012) attempted a study of the effect on the stabilised SWCC of the two physico-chemical properties - pH and surface conduction which are thought to be partly responsible for the development of diffuse double layers in soils. Even though some level of good correlations resulted between the AEV of the SWCC and the two physico-chemical properties, no obvious mechanism could reveal the reason for the effect of pH and the surface conductance.

9.4. Soil type

Wen et al. (2015) compared the behaviour of the SWCC of two soil types – clay and silt, stabilised by the addition of 10% fly ash by dry weight of soil. Both stabilised clay and silt were compacted at a moisture content of 12% and then subjected to suction measurements using the dew point WP4 device. The observed AEV for stabilised clay was greater than that of the stabilised silt. This result was attributed to the stabilised clay smaller pores and greater plasticity compared to those of the stabilised silt. It also invariably meant that the stabilised clay could retain more water than the stabilised silty soil.

10. SWCC vs volume change

Volume change is a macro-scale engineering behaviour that demonstrates soil's response to stress changes and as such, it plays an important role in the soil–water retention capacity of soil (Zhai et al., 2020b, a). It was previously stated that SWCC depends on several initial conditions not least the dry density and moisture content. However, during desorption or absorption, a soil may be subjected to tangible volume changes under the effects of suction and/or imposed effective stress. This phenomenon can be presented as a relationship between void ratio and suction/effective stress thus, forming part of a 3-dimensiinal constitutive surface or space representation of water content – suction/effective stress – void ratio relationships (Fig. 7).

Stoltz et al. (2012) examined the impact of imposed suction-loading (vapor equilibrium and osmotic techniques) on compacted lime-treated expansive clay on both wetting and drying paths of the retention curve. Treatment with lime (2% by dry weight of soil) reduced volumetric expansion (from 17% to 5%) on the hydration path with suction applied under 1100 kPa initial suction of as-compacted samples. Further reduction was observed with increase in binder content. On the drying path, lime treatment reduced shrinkage only minimally (from 20% to 16%) for suctions (up to and beyond 8 000 kPa). Increase in lime content did not bear any significant effects on the shrinkage process. Similarly, Zhang et al. (2017) observed that at very high levels of suctions (approximately above 20,000 kPa), London clay treated with 4% of lime does not have any significant influence on the desorption curve, even though the overall shrinkage/void ratio change due to lime treatment was less compared with the untreated soil. An investigation of initial moisture content indicated that two lime-treated clays (having similar dry densities) with one compacted wet of optimum (higher moisture content) tends to be more deformable (with higher shrinkage volumetric strains) (Fig. 8a) than that compacted on the dry side of optimum (lower moisture content) (Zhang et al., 2017). At the same moisture contents however, the treated soil compacted at lower dry density exhibits slightly higher strains compared to that compacted at higher dry density (Fig. 8b). Overall, Stoltz et al. (2012) and Zhang et al. (2017) observed only minimal influences of extended curing duration on the volume change paths (swelling and shrinkage) upon lime treatment. Zhang et al. (2017) also noted that, the void ratio vs suction curves of their investigated lime treated soil (just like the untreated soils), showed hysteresis hence, denoting the non-recoverability of deformation after drying. In comparative terms, curves of the treated soil had little hysteresis whereas there was clear hysteresis for

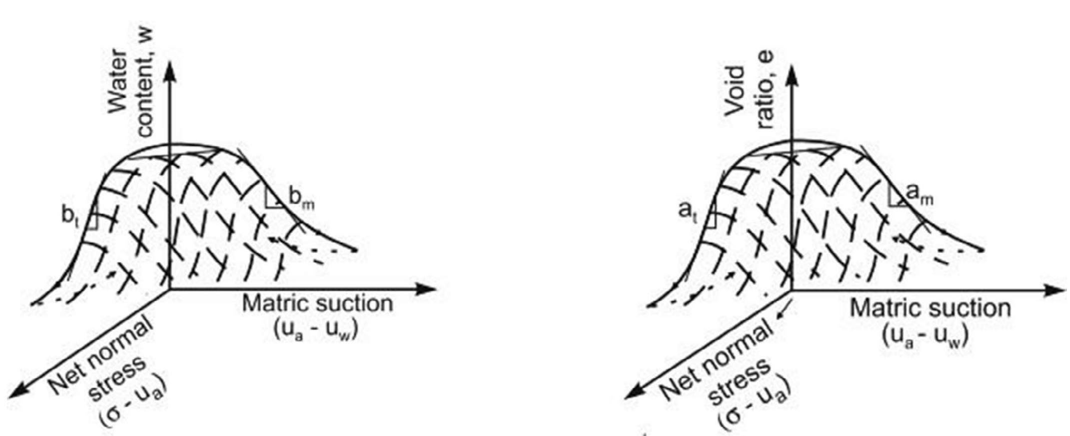

Fig. 7. Water content and Void ratio constitutive surfaces for an unsaturated soil modified after Fredlund (2000).

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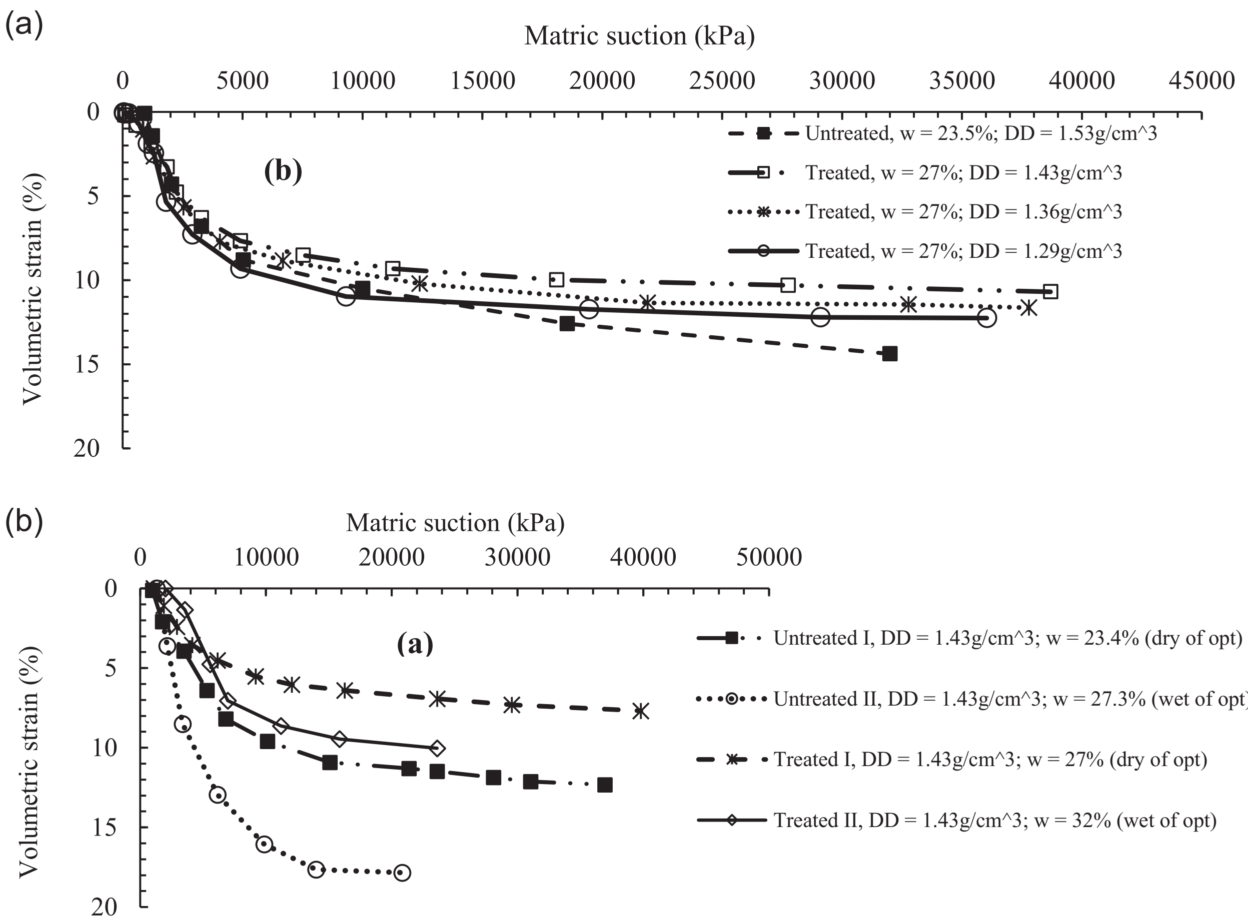

Fig. 8. Effect of initial conditions on volumetric response of SWCC of natural and stabilised soil (a) Effect of initial water content (b) Effect of dry density modified after Zhang et al. (2017).

the untreated soil indicating the difference in void ratio/volumetric changes with water content during drying and shrinkage.

In terms of binder quantity, similar trend of lack of influence of increased binder content on the drying path (desorption) noticed by Stoltz et al. (2012), were reported by Elkady et al. (2015) albeit only with the suction applied up to 1500 kPa using the axis translation technique (pressure plate). However, with suction levels higher than 1500 kPa (measured indirectly with a filter paper), appreciable changes in volume were observed (Fig. 9a). Nonetheless, both Stoltz et al. (2012) and Elkady et al. (2015) seem to agree that at extremely higher suctions, void ratio changes in the treated soils are quite comparable to those of the untreated soils given their tendencies to converge.

For a soil of high plasticity treated by lime (6% by dry weight of soil) and a combination of lime with polypropylene fibres, Al-Mahbashi et al. (2020) noted somewhat of an increment in void ratio at suction levels up to 1500 kPa using the pressure plate apparatus (an observation opposite to that of Elkady et al. (2015). It is not clear what would have been the reason for such trend. However, subsequent reduction in the void ratios of the stabilised soil occurred when filter paper was utilised to measure higher suctions (above 1500 kPa).

Elkady et al. (2015) investigated further, the influence of an externally applied loading (effective stress) on void ratio changes with the observation that higher vertical stress could result to increased compressibility for the treated soil (Fig. 9b). More so,

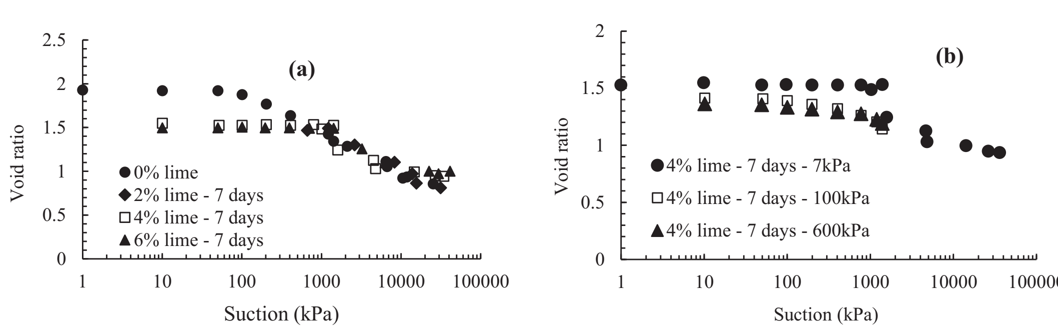

Fig. 9. Volumetric responses of SWCC of natural and stabilised soils (a) Effect of lime proportion on volume change modified after (b) Effect of net stress on volume change of stabilised soil modified after Elkady et al. (2015).

under relatively low net vertical stress, the treated soils tended to experience minimal variation in void ratio hence, causing samples to desaturate more at low levels of suctions (below 1500 kPa in this case). However, Al-Taie et al. (2019) did observe less changes in void ratio of 4% lime-treated soil with increased net "operational" stresses (i.e. excess total vertical stress over the pore air pressure) under increasing suction. Similarly, Zhang et al. (2017) noticed that by using a suction-controlled triaxial apparatus to impose net stresses (on both wetting and drying paths), the deformation of treated samples under a higher mean net stress (200 kPa) was considerably smaller than those subjected to a lesser stress (100 kPa).

Under a different set of circumstances, Mavroulidou et al. (2013) noticed that soils treated with same lime contents can behave differently when subjected to different initial saturation and curing methods before subsequent suction measurement on the desorption path of the SWCC. They observed that the treated soil (4% lime by dry weight of soil) initially made to swell freely (unconfined saturation) during curing (28 days in this case) can exhibit significant changes in void ratios compared to that cured under confined conditions before suction measurements upon drying. Although, when compared to the untreated soil (under initial confined conditions), the initially confined saturated treated soil tended to demonstrate improved volumetric response with both tested within the same suction ranges. Same finding can also be found in the work of Zhang et al. (2017).

An obvious conclusion from the forgoing discussions on volumetric changes under different suction and effective stress ranges is that treatment with binders can enhance volumetric stability of the soil subjected to moisture fluctuations (for example due to seasonal variations). However, it is also crucial to note that even though the hydraulic type binders can prevent swelling upon wetting and probably shrinkage through drying, such treatment may not necessarily lead to a totally stabilised fabric. Stoltz et al. (2012) confirmed this assertion in their investigations using the mercury intrusion porosimetry (MIP) and explained some of the observed modifications that occurred in the treated soil's micro- and macropores when subjected to increasing suction levels. Nevertheless, treatment with other binder types (rather than lime) would be required to further corroborate this claim. Additionally, it may be worth quantifying the variations in volumetric changes caused by the influence of procedures and measurement methodology. This could aid an appraisal of whether such effects are critical for the stabilised soil.

11. Assessment of SWCC of stabilised soils determined from different suction measurement methods

The methods utilised to measure or apply suction can be generally grouped into two major categories – direct and indirect methods. The direct method essentially measures matric suction or negative pore water pressure, since it requires that the equipment's sensor must be in direct contact with the soil. The indirect method (which could be applicable for both matric and total suction measurement) requires that measurement be taken from other parameters like relative humidity (or water content), conductivity, resistivity, etc. for deriving the measured total suction. Several research have establish the variabilities and errors that can be generated in the measurements of natural soil's suction by comparing the equipment used in such measurements (Agus and Schanz, 2007; Nam et al., 2010; Tarantino et al., 2011; Zhai et al., 2020a, 2019). However, a comparison of the methods of suction measurement as applied to stabilised soils is rare in research. Consequently, this section will be focussed on an appraisal of the different suction techniques or approaches adopted by some of the authors in the foregoing discussions. Table 2 presents a summary of the suction measurement techniques used.

11.1. Natural soil

In order to provide the basis for evaluation of the techniques used for the stabilised soils, Fig. 10 indicates the SWCCs of natural soils used by most of the authors cited in this article. Slightly higher variabilities in the data points are observed at the lower suction ranges but as the suction increases, the SWCCs tend to converge. Hence, considering the possible errors emanating from equipment, testing procedure, and natural soils' quality and variability, the resulting SWCCs all seem to be in quite comparable ranges. Nam et al. (2010) and Rahardjo et al. (2018) confirmed this outcome in their studies conducted to compare the SWCC of different soils determined from different suction measurement equipment. Overall, some of the similarities observed in the SWCCs with coincidental suction data points could be as a result of close similarities in attributes such as grain size distribution and consistency limits of the different soils.

11.2. Stabilised soil

Comparison of the techniques utilised by the authors for the measurement of suction of the stabilised soils are now discussed. For the range of suction covered by each of the measurement methods employed by each author, please refer to Table 2.

11.2.1. Stabilisation with same binder proportion

Fig. 11 shows the SWCC (degree of saturation vs suction) of the stabilised soils and the methods of measurements used to measure or apply suction. The extracted suction data were subjected to a nonlinear regression fitting process to obtain the SWCC by using the model proposed by van Genuchten (vG) (Table 1) in order to

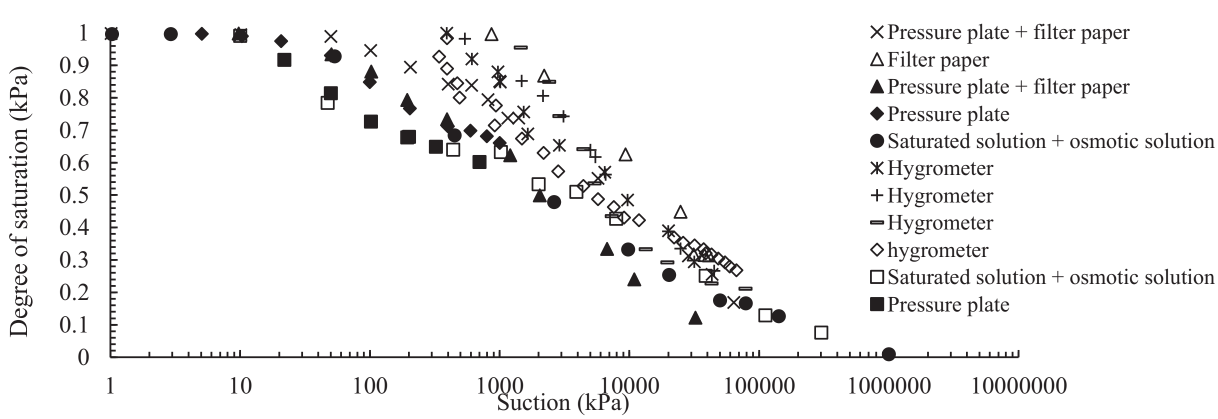

Fig. 10. SWCC of natural soils determined from different suction techniques (modified after authors given in Table 2).

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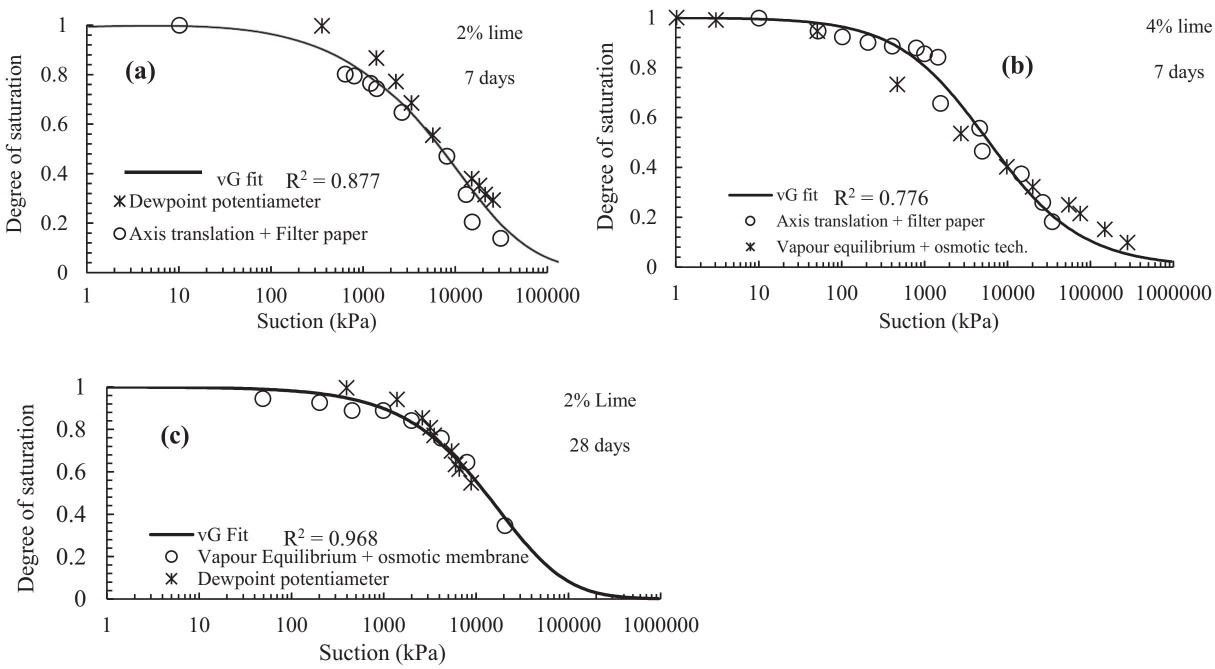

Fig. 11. SWCC of soils stabilised with same binder proportion (a) SWCC determined from dewpoint potentiameter, axis translation and filter paper (modified after Elkady et al. (2015) and Wang et al. (2015) (b) SWCC determined from axis translation, filter paper, vapour equilibrium and osmotic technique (modified after Khattab and Aljobouri (2012) (c) SWCC determined from vapour equilibrium, osmotic technique and dewpoint potentiameter (modified after Stoltz et al., (2012) and Wang et al. (2015)).

enable easier comparison. For the soils (both of which are highly plastic – CH) treated with 2% lime, suction data from a combination of axis translation and filter paper methods appear to be slightly lower than those obtained from dewpoint potentiameter (Fig. 11a). However, the vG fitting model gives somewhat of a good fit (R^2 = 0.877) indicating the little differences in the suction measured from the stated techniques. On the other hand, a combination of four methods (axis translation + filter paper and vapour equilibrium + osmotic membrane) seem to produce a slightly lower coefficient of determination (R^2 = 0.776) when fitted with the vG model for another two of highly expansive clays treated with 4% lime (Fig. 11b). Nonetheless, the closeness of the suction data can still be observed from the four combined techniques utilised. Three measurement approaches applied to measure suction in different ranges (vapour equilibrium + osmotic membrane and dewpoint potentiameter) produced a comparatively very good fit (R^2 = 0.968) for yet another two expansive clays stabilised by 2% of the lime binder (Fig. 11c). It may be too premature to conclude that the results from the different measurement methods presented here are representative of all stabilised soils. Note also that, the mineralogical or chemical differences in the soils used, preparation, curing procedures, etc. may have introduced their own biases. However, it can be said that a combination of both direct and indirect methods could allow quite comparable suction data to be derived. Moreover, it seems an increase in the number of the measurement techniques may generate more errors or inaccuracies and thus produce SWCC with poorer fits.

11.2.2. Stabilisation with different binder proportions

Generally, differences in retention capacity are expected if different amount of the same binder are used for soil stabilisation. Apart from few exceptions, an increase in the amount of a binder used to stabilise a soil would lead to an increase in the soil's moisture retention capacity under the same conditions of testing (Hoyos et al., 2007; Yang et al., 2011). It may also be interesting to examine how the utilisation of different suction measurement or testing equipment might affect this claim for the same soils. Fig. 12 indicate soils stabilised with lime binders and the corresponding SWCCs derived for each different binder proportions using different techniques. It is important to add that the soils used are at least expansive in nature even though they may be fundamentally different in terms of mineralogical and/or chemical compositions. The soil stabilised by 2% lime with its SWCC determined from both the vapour equilibrium and osmotic techniques, seem to show lower retention capacity at relatively low suction (1–1000 kPa) and high suction (100,000 kPa and above) ranges. Nevertheless, the soils stabilised by different binder quantities show high coefficient of determination (Fig. 12a). The axis translation used for soil stabilised by 7% lime is a direct technique and tends to apply suction directly on the stabilised soil compared to the vapour equilibrium (direct) and osmotic (indirect) techniques both of which are used in combination for certain suction ranges. Barring influences from other operational circumstances, it could be observed that the notion of better retention with increased binder may be slightly upheld despite the different suction approaches used. However, for Fig. 12 b-d, the soils stabilised by lower proportion of the binder appear to have more retention of the moisture for most of the suction ranges. Nonetheless, Fig. 12b indicates a higher coefficient of determination (R^2 = 0.933) for the method relying on a combination of axis translation (pressure plate) and filter paper for the determination of SWCC compared to a combination of vapour equilibrium and osmotic techniques (R^2 = 0.863). Also, SWCC derived using the Dewpoint potentiameter tend to have a better fit (R^2 = 0.976) than that which depends on a combination of vapour equilibrium and osmotic techniques (R^2 = 0.863) (Fig. 12c). Meanwhile, the method relying on Dewpoint potentiameter and a combination of axis translation (pressure plate) and filter paper seem to produce SWCCs having high and quite comparable fit as observed by their coefficients of determination (Fig. 12d).

11.2.3. Stabilisation with same proportion of different binders

Because of the apparent insufficient data in literature, further comparisons cannot be drawn from the usage of different methods

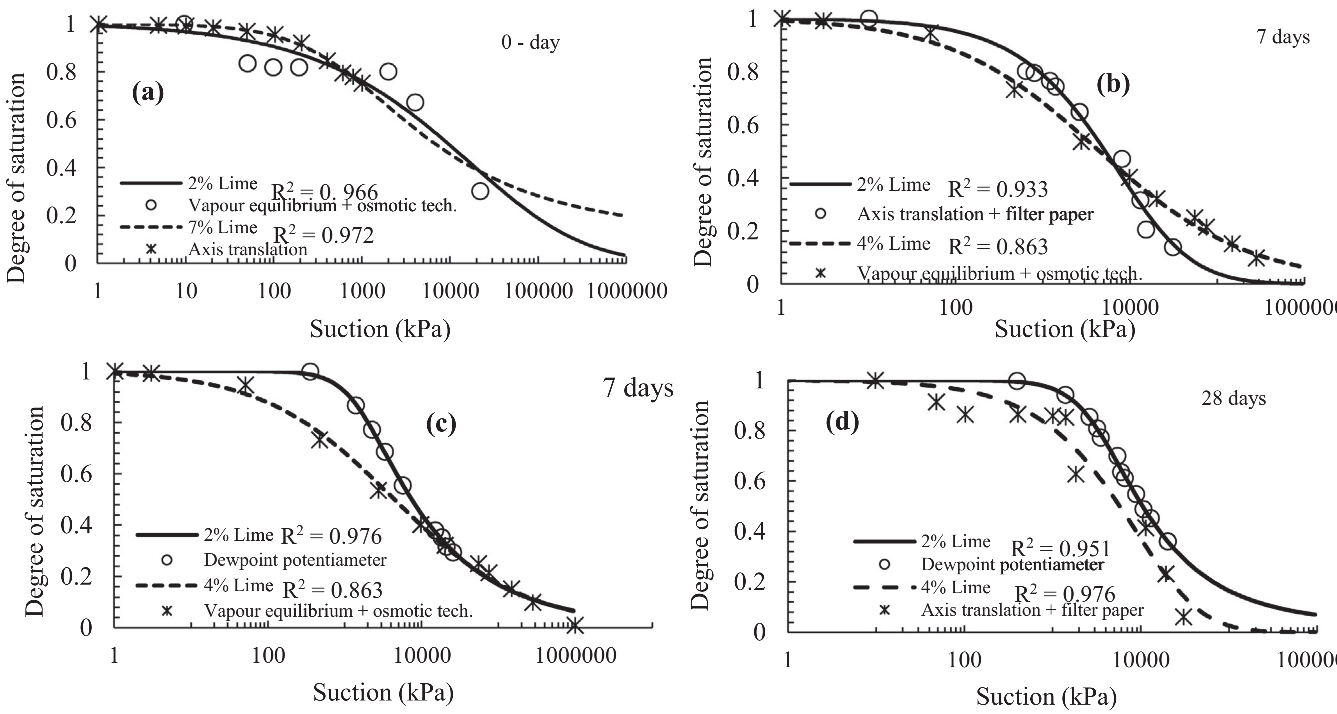

Fig. 12. Effect of different techniques for determination of SWCC of soils stabilised with different binder proportions (a) SWCC modified after (Stoltz et al. (2012) and Yang et al. (2011) (b) SWCC modified after Elkady et al.(2015) and Khattab and Aljobouri (2012) (c) SWCC (modified after Khattab and Aljobouri (2012) and Wang et al. (2015) (d) SWCC modified after Elkady et al. (2015) and Wang et al. (2015).

to determine the SWCC of soils stabilised by different proportions of binders. However, the same procedure of suction measurement applied to examine the SWCC of soils stabilised by different binders were provided in previous discussions but suggestion for future research into different techniques in this regard may not be impractical.

An interesting discovery from an assessment of the measuring techniques employed to derive the SWCCs is that the resulting variabilities in the suction testing or application seem less significant compared to the actual differences in the results of some of the factors that have a bearing on the retention property of the stabilised soils. Both direct and indirect methods can be utilised reasonably well and in combination with each other to obtain SWCC having good fits for the respective suction ranges considered or measured. The subtle differences observed in the utilisation of the techniques could be mostly down to the procedure employed and the operator's skills and competence. However, from the forgoing, it seems in order to achieve very accurate suction data and well fitted SWCC, one would have to rely on techniques that employ the axis translation (pressure plate) and the dewpoint potentiameter.

12. SWCC's fitting parameters

Many curve fitting parameters from SWCC mathematical models developed and proposed by authors can determine the shape or symmetry and position of the SWCC. The *a*-parameter controls the point of inflection on the SWCC and bears a relation to the AEV of the soil. It has been shown that increased stabiliser proportions can cause a rise in the value of the *a*-parameter as the curing time progresses (Lin and Cerato, 2012; Puppala et al., 2006; Zhang et al., 2018). The *n*-parameter indicates approximately the pore size distribution of soils and hence controls the rate of desaturation (or absorption) as soon as the air entry is completed. This fitting parameter relates mainly to the slope portion of the SWCC. Meanwhile, the *m*-parameter relates to the portion of the SWCC that is close to the residual condition (residual moisture content and residual suction). Not many studies have reported on the effects of stabilisers on the *n*- and *m*-parameters still, a few studies have described the influence on both fitting parameters to change according to the stabiliser used but without any clear description of the reasons for any of such behaviour.

13. Conclusions and recommendations for further research

This review article has succinctly presented a comprehensive summary of unsaturated hydraulic characteristics of stabilised soils through a critical examination of their soil–water retention curves. The following are some of the main points emanating from this paper:

1. Treatment or stabilisation can affect a soil's ability to retain moisture by causing a reduction in its initial mass-volume properties (volumetric moisture content, gravimetric moisture content, degree of saturation or void ratio) at low suction (typically for a drying SWCC). Increased moisture retention occurs generally with increase in stabiliser proportion and its fineness. Polypropylene-type stabilisers if used solely in stabilisation may not have much effect on the mass-volume property except if combined with hydraulic-type ones. Moreover, some of the main suction parameters such as air entry value (AEV) and residual suction value (RSV) can increase when the soil is stabilised.
2. The influence of stabilisation on initial compaction states (dry density and initial water content) seem only significant at near saturation portions of the SWCC where capillary forces predominate. Treated soils with higher initial dry densities (DD) retain more water than those of low dry densities. Higher degrees of retention are also noticed for soils compacted wet of optimum than those compacted dry of optimum. However, depending on the method used to derive the hydraulic properties, the symmetrical arrangement of the SWCC for both the treated and

untreated soils may not change if for instance the axis translation method is used to measure suction.

3. Suction-induced volume changes (reduced swelling) can be quite considerable especially on the wetting front or hydration path for the stabilised soil at low suction. However, the effect of treatment on volume change seems minimal on the drying curve with the soil's ability to shrink only affected slightly at higher suctions. Moreover, reduced volume changes due to treatment with binders may not necessarily suggest a totally stabilised fabric.
4. Increased retention and AEV appear to occur with increased curing duration of the stabilised soil mostly in the shorter term. However, the effect of curing can be minimal with prolonged curing presumably due to slowing down of pozzolanic reactions. Depending on the procedure used in the determination of the SWCC, the influenced of curing duration on retention capacity has also been reported by few studies to be almost non-existent.
5. Soil properties can bear some influences on the stabilised soil's SWCC. Increased retention capacity seems to occur is soils having smaller aggregate sizes. Smaller-sized soil aggregates tend to form smaller modal size of the macropores with resulting high AEV compared to the stabilised soil having much larger aggregates. Other inherent factors such as the presence of sulphates, mineral type (clay or silt), soil pH, etc. have been reported to affect the SWCC though with no clearly defined reasons.
6. In terms of procedure, resulting variabilities in SWCC from suction testing or application seem less significant compared to the differences observed from the above-mentioned factors relating to stabilisation. Both direct and indirect methods may be utilised reasonably well and in combination to obtain well fitted suction data points of the SWCC. Any differences attributed to technique could be because of the procedural objective intended and the operator's skill and competence. However, it seems in order to achieve suction data points with high accuracy, techniques such as axis translation (pressure plate) and the dewpoint potentiameter may be used.

Even though some of the fundamental variables that could be considered to influence the behaviour of moisture retention of stabilised soils have been reported in the foregoing, a multiplicity of other factors that include environmental conditions, treatment methods and setup procedures such as impact of freezing and thawing, acidic conditions and other contaminants, soil organic matter content, compaction energy, using and comparing behaviour from a broader range of stabilisers, etc. could also be taken into account in future research. The techniques and concepts used for the determination of the SWCC could be explored and comparisons drawn for treatments under the same conditions to enable a more unified explanation of the behaviour of the hydraulic characteristics of stabilised soils. Other notions such as hysteresis, unimodal or bimodal SWCC, etc. that could accompany the stabilised soil's moisture retention can be examined too. Finally, and very importantly, more studies can be embarked upon to enable better interpretation of engineering properties and behaviour such as shear strength, permeability, consolidation, etc. from the SWCC of stabilised soils vis-à-vis the factors or conditions mentioned above that can influence such relationships.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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